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The NRL LACE Program Final Report

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The Naval Research Laboratory's Low-power Atmospheric Compensation Experiment (LACE) Program was established to provide and operate a satellite that could carry and support instruments to measure the intensity and distribution of low-energy laser beams transmitted from Earth; to image the ultraviolet emission from rocket plumes at high altitudes; and to measure the spectrum and distribution of terrestrial neutrons. The satellite was launched on 14 February 1990. It made many successful laser beam measurements; collected high-quality emission images from four rocket launches in four attempts; and made neutron background measurements almost continuously for 36 months.

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EXECUTIVE SUMMARY

The Naval Research Laboratory's Low-power Atmospheric Compensation Experiment (LACE) Program was sponsored by the Strategic Defense Initiative Organization (SDIO). The objective of the NRL LACE Program was to provide and operate a satellite to carry and support:

- a sensor array subsystem (SAS) to measure at the satellite, as a function of time and spatial distribution, the absolute intensity of low-energy ultraviolet, visible, and infrared laser beams transmitted from ground laser sites;
- the Ultraviolet Plume Instrument (UVPI) to obtain ultraviolet images of plumes from rockets and to obtain ultraviolet background and clutter data over a wide variety of spatial, temporal, and lighting conditions;
- the U. S. Army Strategic Defense Command's Army Background Experiment (ABE) to measure, as a function of geomagnetic latitude, the neutron background spectrum and the angular distribution of terrestrial neutrons; and
- the U. S. Air Force's (USAF) Radiation Detection Experiment (RDE) to measure electromagnetic radiation.

In February 1985, SDIO representatives came to NRL to discuss the possibility of an instrumented target satellite for measuring the propagation of laser beams from the ground to space. The concept required the development of one simple sensor to be carried aboard a host satellite. On 14 February 1990, the LACE spacecraft was launched as a 3175-lb satellite carrying three sophisticated arrays of laser sensors, a precision pointing and imaging instrument, and a neutron background monitoring instrument for SDIO and a USAF instrument. At launch, additional NRL LACE Program assets included one permanent ground station and two transportable ground stations, a high-fidelity test bed, an operations control center, and a data processing and assessment center.

After launch, many SAS operations were conducted in support of the Massachusetts Institute of Technology Lincoln Laboratory's Short Wavelength Adaptive Techniques (SWAT) Program for compensation of atmospheric-induced distortions of ground-based laser beams. A completely successful cooperative atmospheric compensation demonstration was first achieved on 30 November 1990. Many more successful demonstrations and tests were conducted until the SWAT Program was completed in April 1991. The UVPI collected high-quality ultraviolet emission images from four rocket launches in four attempts, as well as large quantities of Earth background data. The ABE made highly successful measurements of the neutron background in space almost continuously following launch. The RDE made measurements over 14 months.

In response to SDIO's request, operations with the LACE satellite were terminated on 14 February 1993. The satellite had successfully accomplished its mission.

The LACE satellite was left in a stable configuration so its retroreflector array can be used as a target. The length of the leading boom was left at 15 ft. Therefore, until the momentum wheel fails, the retroreflector array will lead the spacecraft's main body. After the momentum wheel fails, the retroreflector array will be 15 ft from the main body in an unknown direction.

THE NRL LACE PROGRAM FINAL REPORT

1.0 NRL LACE PROGRAM CHRONOLOGY

In February 1985, representatives of the Strategic Defense Initiative Organization (SDIO) came to the Naval Research Laboratory (NRL) to discuss the possibility of an instrumented target satellite for measuring the propagation of laser beams from the ground to space. The spaceborne target was needed to determine the viability of atmospheric compensation techniques being developed at the Massachusetts Institute of Technology Lincoln Laboratory (MIT/LL) under SDIO sponsorship. The concept required the development of one simple sensor to be carried aboard a host satellite. Subsequently, in July 1985, the NRL LACE Program began as the Laser Communication Experiment (LACE). This experiment called for a single sensor to detect infrared (IR) laser emission and flown on NASA's shuttle-launched Long Duration Exposure Facility (LDEF) satellite. The LDEF was then in orbit and scheduled to be retrieved by the shuttle. Since LDEF was a completely passive satellite, supporting subsystems (such as electrical power and communications) would have to be added. As a result of the Challenger accident and the subsequent interruption in shuttle launches, it became clear that the LDEF was not likely to be available as a structure for LACE. Therefore, by June 1986, LACE had become a full satellite itself instead of a sensor complement to be flown on LDEF. The name was changed to Low-power Atmospheric Compensation Experiment (LACE). Launch was scheduled for August 1988.

By June 1986, the sensor requirements had been expanded to include multiple sensors to detect IR laser emission and additional sensors to detect emission from continuous wave (CW) and pulsed lasers emitting in the visible and ultraviolet (UV) bands. Ultimately, 210 sensors in three arrays distributed over a 4 m by 4 m target board were launched as the sensor array subsystem (SAS).

The additional ground-based lasers that would use the LACE satellite as a target were located at widely separated sites. Therefore, transportable ground stations (TGS) had to be developed to provide the communications links between the ground laser sites and the satellite

The Army Background Experiment (ABE), an instrument package that was to be developed for SDIO by the Los Alamos National Laboratory (LANL), was added to the LACE satellite's experiment complement. The Radiation Detection Experiment (RDE), an instrument package to be developed for the U. S. Air Force (USAF) by The Aerospace Corporation, was also added.

To support the atmospheric compensation tests, a requirement was added for a retroreflector array. It was to have 252 cornercubes mounted on the end of a boom that could be extended up to 150 ft from the satellite body. Variable length booms had never been flown for more than a few days in space. The LACE satellite has three variable length booms, which can each be extended up to 150 ft.

In April 1987, SDIO decided that the Ultraviolet Plume Instrument (UVPI) would be added to the LACE satellite. This forced a major redesign of mechanical and electrical subsystems. As an example, the addition of the UVPI, which is a precision pointing instrument, invalidated key decisions relating to the spacecraft's attitude measurement. As a result, a third type of attitude measurement sensor had to be

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added to the satellite and an extensive study conducted to ensure that the attitude of the gravity-gradient stabilized LACE satellite could be predicted accurately over several hours. The addition of the UVPI also meant that the NRL LACE Program would be responsible for extensive mission planning and for the processing of significant amounts of sensor data. Prior to the addition of the UVPI, mission planning for the LACE satellite's operations was very simple, and all data were to be quickly turned over to MIT/LL, LANL, or The Aerospace Corporation for processing. Launch was still scheduled for August 1988.

In early 1988, the Delta launch vehicle assigned to the NRL LACE Program was assigned to a higher priority SDIO mission, Delta Star. From then until January 1989, a number of changes were made by SDIO in the assignment of a launch vehicle. A Titan, Atlas, and Delta again were real contenders. They each had sufficient credibility that the LACE satellite's electrical and mechanical mounting interfaces were redesigned to accommodate each designated launch vehicle. A second satellite, the Relay Mirror Experiment (RME), was added to the launch manifest, and the NRL LACE Program was given launch vehicle integration responsibility for both LACE and RME satellites.

In summary, the NRL LACE Program started with a requirement for a simple instrumented target with a single sensor on NASA's shuttle-launched LDEF spacecraft. On 14 February 1990, the LACE spacecraft was launched as a 3175-lb satellite carrying three sophisticated arrays of laser sensors, a precision pointing and imaging instrument, and a neutron background monitoring instrument for SDIO and a USAF instrument. At launch, additional NRL LACE Program assets included one permanent ground station (PGS) and two TGSs, a high-fidelity test bed, an operations control center, and a data processing and assessment center.

After the LACE satellite became fully available to users in mid-April 1990, many SAS operations were conducted in support of MIT/LL's Short Wavelength Adaptive Techniques (SWAT) Program for compensation of atmospheric induced distortions of ground-based laser beams. A completely successful cooperative atmospheric compensation demonstration was first achieved on 30 November 1990. Many more successful demonstrations and tests were conducted until the SWAT Program was completed in April 1991.

The UVPI collected high-quality UV emission images from four rocket launches in four attempts, as well as large quantities of Earth background data. The UV images of rocket plumes from UVPI are essential to SDIO's development of valid computer models that can accurately predict the emission characteristics of any rocket plume and to SDIO's evaluation of the feasibility of using the UV emission from a rocket plume to locate the rocket itself.

The ABE made highly successful measurements of the neutron background in space almost continuously following launch. The ABE data provide information useful to SDIO for designing spaceborne systems to discriminate warheads from decoys.

The RDE made measurements over 14 months, and all data were turned over to The Aerospace Corporation for evaluation.

In early 1993, SDIO decided that the LACE satellite had achieved its objectives and requested that operations involving the satellite be terminated. The last operations with the LACE satellite occurred on 14 February 1993. The LACE satellite was left in a stable configuration so its retroreflector array can be used as a target. The length of the leading boom was left at 15 ft. Therefore, until the momentum wheel fails, the retroreflector array will lead the spacecraft's main body. After the momentum wheel fails, the retroreflector array will be 15 ft from the main body in an unknown direction. The final lengths of the

gravity-gradient boom and the trailing boom were 100 ft. Electrical loads were distributed between the two batteries in an attempt to allow the electric power subsystem to support the spacecraft unattended for as long as possible.

2.0 PROGRAM OBJECTIVE

The objective of the NRL LACE Program was to provide and operate a satellite to carry and support:

- a SAS to measure at the satellite, as a function of time and spatial distribution, the absolute intensity of low-energy UV, visible and IR laser beams transmitted from ground laser sites;
- SDIO's UVPI to obtain UV images of plumes from rockets and to obtain UV background and clutter data over a wide variety of spatial, temporal, and lighting conditions;
- the U. S. Army Strategic Defense Command's (USASDC) ABE to measure, as a function of geomagnetic latitude, the neutron background spectrum and the angular distribution of terrestrial neutrons; and
- the USAF's RDE to measure electromagnetic radiation.

Specific NRL responsibilities for the LACE Program included:

- LACE satellite design, fabrication, integration, testing, launch, and operation;
- SAS design, fabrication, testing, calibration, integration, and operation;
- UVPI design, fabrication, testing, calibration, integration, and operation;
- ABE integration and operation;
- RDE integration and operation;
- planning UVPI observations and quick-look data assessment; and
- ground station design, fabrication, testing and operation.

3.0 THE LACE SATELLITE

The LACE satellite was designed and built by the Naval Research Laboratory (NRL) in Washington, DC. Responsibility for significant portions of the spacecraft design, especially its mechanical design, was contracted to Fairchild Space Company. The satellite (Fig. 1) was successfully launched from Florida aboard a Delta II launch vehicle on 14 February 1990. The main body of the satellite is box shaped, with dimensions of 4.5 ft by 4.5 ft by 8 ft high. A 150-ft-long boom with a 200-lb tip mass and magnetic damper extends from the top, space-facing surface of the satellite's main body to provide gravity-gradient stabilization. Solar panels on the main body and deployed solar panels around the space-facing end provide energy to the spacecraft. Energy storage is accomplished by two nickel-cadmium batteries. Deployed sensor panels and the Earth-facing end of the main body provide a 4 m by 4 m target board for the SAS. Many SAS sensors and the ABE sensor are mounted on the deployed sensor panels. The UVPI and RDE are mounted internally on the Earth-facing end of the main body. A leading boom, variable in length up to 150 ft, has a retroreflector array at its end. This boom is held in the spacecraft's velocity direction by a momentum wheel inside the spacecraft stiffening the yaw and roll orientations. A trailing boom in the anti-velocity direction, also variable in length up to 150 ft, permits the spacecraft's moment of inertia about its pitch axis to be held constant as the length of the leading boom is changed to support test requirements. The LACE spacecraft has no onboard propulsion capability for orbital changes or for attitude control. A very-high-frequency (VHF) ground-to-spacecraft command link operates at a data rate of 1 kilobit per second (kbps). The spacecraft-to-ground data link operates in S-band at a rate of 3.125 megabits per second (Mbps). The spacecraft has two visible-band strobe lights that can be commanded to

flash with a fixed period between 3 and 4 s to help users find the satellite. One of these strobe lights failed a few months after launch.

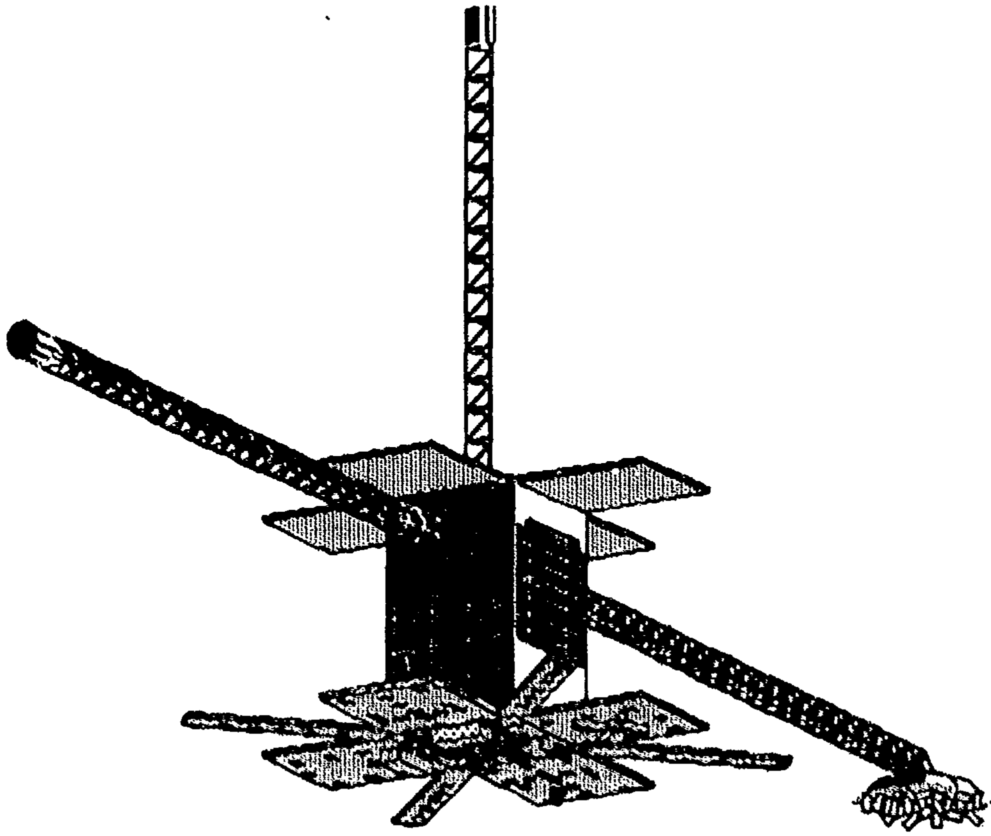

Fig. 1- Schematic of LACE satellite

3.1 Orbit

The satellite's initial orbit was nearly circular, with an altitude of 292 nautical miles (nmi) [541 kilometers (km)] and an orbital inclination of 43.1°. The altitude was constrained by the retroreflector array and stability requirements. The maximum altitude at which the retroreflector array could return an adequate signal to the laser site was 300 nmi. The minimum altitude at which atmospheric effects could be overcome to hold the tip of the fully extended leading boom within 2 ft of the centerline of the spacecraft was 230 nmi. Therefore, the initial altitude could not exceed 300 nmi, but it had to be high enough to ensure that the altitude would not decay to 230 nmi during the 30-month planned lifetime of the spacecraft. At launch, an altitude of 295 nmi was the goal. The initial altitude attained was within the error limits of the launch vehicle.

A constraint on both the inclination and altitude of the orbit was the frequency of usable passes over each ground laser site. For atmospheric compensation tests, the satellite had to be at an elevation greater than 45° from the laser site for at least 1 min. Approximately one usable pass per day was desired for the laser sites in Hawaii, Massachusetts, and New Mexico throughout the 30-month planned lifetime of the

spacecraft. At launch, an inclination of 43.0° was the goal. The inclination attained was within the error limits of the launch vehicle.

By late November 1992, the altitude of the LACE satellite had decayed to 259 nmi. Based on late 1992 predictions of solar activity, reentry of the LACE satellite is estimated to occur in 1999.

4.0 GROUND SUPPORT ELEMENTS

4.1 Ground Stations

The NRL LACE Program operated three ground stations that provided all of the communication links with the LACE spacecraft. Two of the three ground stations were transportable because SAS operations required, and UVPI operations benefited from, real-time data. One TGS was stationed in Maui, Hawaii, for the entire LACE mission. The second TGS was mounted on wheels and supported LACE from Malabar Air Force Station, Florida, and Vandenberg Air Force Base (AFB), California. Each TGS consisted of two 18-ft truck trailers. One trailer contained telemetry, command, communications, data handling, and data display equipment. The second trailer contained an uninterruptable power supply, a work area, and supporting equipment. The 12-ft-diameter antenna could be stowed in the trailers for transporting. The third LACE ground station, the PGS, was located in Maryland.

4.2 LACE Operations Control Facility

The LACE Operations Control Facility (LOCF) was a dedicated NRL LACE Program facility that established spacecraft and ground station activity schedules, monitored the status of the LACE spacecraft, interacted with the ground stations during spacecraft passes, and managed the data from the spacecraft. The LOCF was located in Alexandria, Virginia.

4.3 UVPI Mission Planning and Assessment Center

The UVPI Mission Planning and Assessment Center (UMPAC) was a dedicated NRL LACE Program asset that planned all use of the UVPI, defined and tested all command sequences for the UVPI, executed UVPI observations, processed all UVPI data, assessed the results of all UVPI observations, monitored the calibration of the UVPI, and deposited processed and unprocessed UVPI data into SDIO archival data centers. The UMPAC was also located in Alexandria, Virginia.

4.4 LACE Operational Test Bed

The LACE Operational Test Bed (LOTB), collocated with the LOCF and the UMPAC, was a high-fidelity simulator for the LACE spacecraft and its ground stations. The LOTB was used to test all command sequences before they were sent to the spacecraft to ensure that the commands would produce the desired response in the spacecraft. The LOTB was also used to investigate anomalies noted in the spacecraft or ground stations.

4.5 UVPI Ground Beacons

Four 1500-W output and one 750-W output beacons served as portable ground targets for the UVPI. These beacons were used as targets with precisely known locations to test pointing control and to measure optical characteristics, such as point spread function, of the UVPI cameras. The beacons could be used together to increase the illumination, or separated to support multiple tests. They could be deployed in

patterns to test the spatial resolution of the UVPI. They were also used in all rehearsals for rocket plume observations during which they were turned on and off to simulate the various stages of the rocket.

5.0 SPACECRAFT SENSOR COMPLEMENT

5.1 Sensor Array Subsystem

The SAS, designed and built for NRL by Instrumentation Technology Engineering (ITE) Incorporated, has three arrays of electro-optical sensors (visible, pulsed, and IR), with each array sensitive to different types of laser radiation. Only one of the three arrays can be active at any time. The field of view of each sensor of each array is a 45° half-angle cone centered on the normal to the spacecraft's target board. Since the normal to the target board is held to within 3° of the nadir direction, the SAS measures laser beams from ground-based sites that are within approximately 45° of the spacecraft nadir and at any azimuth angle. Several data sampling modes can be selected for the various SAS arrays. Some sampling modes are free running. Some use ground-based triggering lasers to synchronize the scoring laser emission with the data sampling sequence aboard the spacecraft. Narrowband triggering detectors aboard the spacecraft detect the triggering laser emission and start the selected sampling cycle. There is no provision for storage of SAS data aboard the LACE spacecraft. SAS data must be transmitted to the ground in real time as it is generated by the SAS sensors.

All three SAS arrays were turned on in November 1992 to compare their condition with that observed during initial activation after launch. No degradation was found.

Visible Sensor Array

The visible sensor array consists of 85 sensors distributed over the 4 m by 4 m target board on the Earth-facing end of the spacecraft, with the greatest density of sensors at the center of the target board. The visible array was specifically designed to measure laser emission from the SWAT Program's argon ion laser located in Maui, Hawaii. Calibration of the visible array sensors was done at 514.5 nanometers (nm), which was the emission wavelength of the SWAT Program's laser. However, the visible array sensors are sensitive over a waveband from approximately 400 nm to approximately 1.06 micrometers (μm). After launch, a less precise calibration of the visible array sensors was done at 1.06 μm by using spare sensors. This special calibration was done to support the USAF Starfire Optical Range at Kirtland AFB, New Mexico. To be measured by the visible sensor array, the laser emission must be CW modulated at 25 kHz ± 10 Hz with a square-wave or sinusoidal pattern.

Each visible array sensor is a silicon photodiode with sapphire and rutile, TiO_2, windows. Based on calibration of the sensors at 514.5 nm by using square-wave modulation with a 50% duty cycle, the dynamic range of the visible sensor array is from 58 nW/cm^2 to 9.6 mW/ cm^2.

Pulsed Sensor Array

The pulsed sensor array consists of 85 sensors, each located in the same housing with a visible array sensor. The pulsed sensor array was not designed to support any particular existing laser, but to generally support pulsed excimer lasers in the 300 to 400-nm wavelength band and a low-power emulator of the free electron laser with pulsed emission at 1.06 μm. The pulsed array sensors were calibrated at 354 nm and at 1.06 μm. However, the pulsed array sensors are sensitive over a waveband from approximately 300 nm to 1.06 μm. To be measured by the pulsed sensor array, the pulsed emission must have a pulse duration between 10 nanoseconds (ns) and 2 microseconds (ms) and a pulse repetition rate of 100 pulses per second or less.

Each of the pulsed array sensors is composed of two UV-enhanced silicon photodiodes with sapphire windows and different neutral density filters to provide the required dynamic range. Based on calibration of the sensors at 354 nm, the dynamic range of the pulsed sensor array is 20 nJ/cm^2 to 1.6 mJ/ cm^2. Based on calibration at 1.06 μm, the dynamic range is 5 nJ/cm^2 to 0.4 mJ/ cm^2.

Infrared Sensor Array

The IR sensor array consists of 40 sensors uniformly distributed over the 4 m by 4 m target board on the Earth-facing end of the spacecraft. The IR array was specifically designed to measure laser emission from the Low Power Chemical Laser (LPCL) located at White Sands, New Mexico. The LPCL is a deuterium fluoride chemical laser that produces emission as several lines with wavelengths between 3.6 and 4.2 μm. The IR array sensors were calibrated by using a blackbody source filtered to provide a bandpass between 3.6 and 4.0 μm. To be measured by the IR sensor array, the laser emission must be CW and chopped at 1440 Hz.

Each of the IR array sensors is composed of two HgCdTe photoresistive detectors with sapphire, germanium, and silica windows. The two detectors are held at different temperatures, -30° and 10° C, by Peltier coolers and resistive heaters to provide adequate dynamic range within each sensor. Based on calibration of the sensors using a bandpass between 3.6 and 4.0 μm, the dynamic range of the IR sensor array is from 160 nW/cm^2 to 7.5 mW/ cm^2.

Sensor Calibration

All 210 sensors, each with five orders of magnitude dynamic range, were calibrated against laser wavelength, angle of incidence in elevation and azimuth, polarization, and for sensor temperature. Absolute sensor calibrations to 10% accuracy were required. The calibration effort took well over a year, usually using two shifts a day, and was conducted by Physical Sciences Incorporated, now Research Support Instruments, under contract to Fairchild Space Company.

Boom-Mounted Retroreflector Array

An array containing 252 cornercube retroreflectors is mounted on the end of a variable length boom that is held in the velocity direction of the spacecraft. The length of the boom can be adjusted in flight between approximately 3 ft and 150 ft. The retroreflector array's primary purpose was to support cooperative atmospheric compensation tests. During a cooperative atmospheric compensation test, an illuminating laser beam from the ground laser site was retroreflected by the array to send an undistorted beam back toward the ground laser site. Distortions caused by the downward passage through the atmosphere were measured at the ground laser site and the next transmission of the scoring laser beam was compensated to correct for the measured distortions in the reflected illuminating beam. Ideally, the length of the boom is set so that during the time between the reflection of the illuminating beam from the retroreflector array and the arrival of the compensated scoring beam at the spacecraft, the spacecraft will have moved the length of the boom and the compensated scoring beam will strike the target board. This phasing allows the compensated scoring beam to transit the same column of atmosphere that was measured by the reflected illuminating beam. Spacecraft dynamics require that the length of this boom be continuously changed during an atmospheric compensation test. Motors to drive the boom fast enough to maintain the optimal length were not available in time to meet the LACE satellite's launch schedule, so the boom was not moved during a test. Therefore, the boom was at the ideal length for only a short portion of each test.

The retroreflector array comprises three different types of 1-in.-diameter cornercube retroreflectors: solid glass, solid germanium, and open. There are 240 solid glass cornercubes made of BK-7 optical glass. They can be used in the wavelength band between 350 nm and 2.0 μm. One solid germanium cornercube is intended for use with a 10.6 μm wavelength laser. There are 11 open cornercubes whose aluminum reflecting surfaces work well for wavelengths from 200 nm to beyond 20 μm.

The 252 cornercubes are arranged in a pattern to provide retroreflection for laser beams from ground sites at any azimuthal direction and for which the satellite's elevation is greater than 45°.

5.2 Ultraviolet Plume Instrument

The UVPI was designed and built for NRL by Loral Electro Optical Systems under contract to Fairchild Space Company. Fairchild Space Company also provided significant system engineering for the UVPI. The instrument is mounted within the spacecraft and looks through an aperture in the Earth-facing end. When the UVPI is not in use, a door covers the aperture. The UVPI's mission is to obtain radiometrically calibrated images of rocket plumes at high altitude and background image data of Earth, Earth's limb, and celestial objects in the near and middle UV wavebands. The UVPI was designed for nighttime observations, that is, to acquire and track relatively bright objects against a dark background.

Two coaligned, intensified charge-coupled device (ICCD) cameras are used in concert to locate the object of interest, control UVPI, and obtain images and radiometric data. The tracker camera and the plume camera share a fixed 10-cm diameter Cassegrain telescope that uses a gimbaled plane steering mirror to view a field of regard that is a 50° half-angle cone about the spacecraft's nadir. Additionally, a plane mirror on the instrument's door can be used with the steering mirror to extend the UVPI's field of regard to view Earth's limb and stars near the limb in a southerly direction.

The tracker camera has a relatively wide field of view of 2.0° by 2.6° and a single bandpass of 255 to 450 nm. The tracker camera has three primary functions:

- its wide field of view and bright image are used to find the object of interest;
- images from the tracker camera can be processed within UVPI and the results used to control the gimbaled mirror for autonomous tracking of the target; and
- the tracker camera is calibrated and, therefore, it can obtain radiometric data within its bandpass.

The plume camera has a much narrower field of view, 0.18° by 0.14°, and has a correspondingly higher resolution than the tracker camera. The plume camera has a four-position filter wheel to provide four bandpasses: 195 to 295 nm, 220 to 320 nm, 235 to 350 nm, and 300 to 320 nm. Only one bandpass can be selected at a time. The purpose of the plume camera is to obtain high-resolution images and radiometric data within its bandpasses.

Images are digitized and can be immediately transmitted to the ground, stored in the UVPI's digital tape recorder for later transmission, or both. The transmission or storage rate is 5 images per second if the full fields of view of the cameras are selected, or 30 images per second if reduced fields of view are selected. For each camera, the reduced field of view is approximately 17% of the full field of view. Each camera has a radiometric dynamic range greater than 10^6.

In a typical operation for a rocket plume observation, the UVPI was programmed by ground command to dynamically point the gimbaled mirror so the tracker-camera's field of view contained the expected location of the plume. A selected scan pattern was superposed on the dynamic pointing

trajectory until the target plume entered the field of view of the tracker camera. The tracking control electronics within the UVPI then locked on the target plume and took over control of the gimbaled mirror to bring and keep the rocket plume near the center of the plume camera's field of view. Both cameras then gathered image and radiometric data. The plume camera's filter wheel was rotated during the observation to change bandpasses. If the target plume was lost because of coasting between stages or for other reasons, the UVPI could use extrapolation or search modes to try to lock on the target again.

Radiometric calibration of the UVPI was done before launch and confirmed after launch by star observations. Stars of known emission spectrum based on measurements by other spaceborne sensors were used for post-launch verification. The calibration values obtained by using the stars are close to the calibration values obtained before launch. Calibration based on the star measurements is used as the primary calibration of the instrument. Reference 1 provides a complete description of the calibration of the UVPI.

The UVPI was operated for the last time in early February 1993 to find out if it was still working properly. It operated normally. The data were not saved. It is interesting to note that the commercial video cameras used in the UVPI, which were modified only slightly for use in space, functioned successfully for three years in space.

An NRL report describing the UVPI [2] is being widely distributed to SDIO, to UVPI data users, and within the NRL LACE Program.

5.3 Army Background Experiment

ABE started out as the Neutron Background Experiment but its name and acronym were soon changed (possibly in the hope of capturing the attention of SDIO's first director, Lt. Gen. James A. Abrahamson). The purpose of ABE was to measure, as a function of geomagnetic latitude, the neutron background spectrum and the angular distribution of terrestrial neutrons. These data provide information useful for designing spaceborne systems to discriminate warheads from decoys.

The ABE instrument package was designed, assembled, tested, and calibrated for SDIO by LANL under the sponsorship of USASDC. The sensor is mounted on one of the deployed sensor panels on the Earth-facing end of the spacecraft.

5.4 Radiation Detection Experiment

The RDE is sensitive to electromagnetic radiation. The instrument package was designed, assembled, tested, and calibrated for the USAF by The Aerospace Corporation. The RDE sensor is mounted internally on the Earth-facing end of the spacecraft's main body and looks in the nadir direction through an aperture.

6.0 PROGRAM ACCOMPLISHMENTS

6.1 SAS-Related Accomplishments

Atmospheric Compensation Tests

Many SAS operations were conducted in support of the MIT/LL SWAT Program for compensation of atmospheric induced distortions of ground-based laser beams. After several months of normal developmental interaction between the ground-based SWAT system and the spaceborne SAS with only

partial successes, a completely successful cooperative atmospheric compensation demonstration was achieved on 30 November 1990. Although previously accomplished in a laboratory environment, this proved that atmospheric compensation would work with a real spacecraft at ranges of hundreds of kilometers and at orbital velocities. After the initial success, many more successful demonstrations and tests were achieved; the SWAT Program was completed in April 1991. Successful atmospheric compensation is essential to the use of ground-based lasers for strategic defense.

Cooperative atmospheric compensation tests with the LACE satellite could use two or three ground-based lasers: an illuminating laser, a scoring laser, and sometimes a triggering laser. An illuminating laser beam was transmitted to the retroreflector array on the spacecraft's leading boom. The retroreflector array sent an undistorted beam back toward the laser site. Distortions caused by the downward passage through the atmosphere were measured at the laser site, and the scoring laser beam was compensated to correct for the measured distortions in the reflected illuminating beam. When synchronization between the scoring beam and the SAS data sampling sequence was required, transmission of the compensated scoring beam was preceded by transmission of a pulse from the triggering laser. Ideally, the length of the leading boom is set so that during the time between the reflection of the illuminating beam from the retroreflector array and the arrival of the compensated scoring beam at the spacecraft, the spacecraft will have moved the length of the boom, and the compensated scoring beam will strike the target board. This allows the compensated scoring beam to transit the same column of atmosphere that was measured by the reflected illuminating beam. This sequence of beams is repeated rapidly. The SAS measured the intensity and distribution of the scoring beam over the 4 m by 4 m target board, and this information was transmitted in real time to the TGS, which immediately relayed it to the laser site. The SAS data was immediately processed and displayed in the laser site and used to adjust the aim of the scoring laser. Later, more detailed analysis of the SAS data by the SWAT Program revealed the effectiveness of the atmospheric compensation technique used for each test. The SAS data also provided information on atmospheric turbulence and its effect on beam propagation, and a measure of tracking accuracy and jitter for the laser beam director and its stabilization system.

In general, there was only one pass per day for which the spacecraft was at an elevation above 45° from the SWAT laser site in Hawaii. The time during which the elevation was above 45° and atmospheric compensation testing could be done was rarely greater than two minutes per day.

Figure 2, provided by the MIT/LL's SWAT Program, shows the qualitative effect of successful atmospheric compensation. Each line intersection in the profiles represents the location of a visible array sensor on the LACE satellite's target board. The top beam profile shows that the energy in the uncompensated scoring beam is diffuse, and the beam energy at any point on the target board is small. The bottom image shows that the energy in the compensated beam is highly concentrated near the center of the target.

A report published by the SWAT Program [3] describes their atmospheric compensation tests using the LACE satellite.

Retroreflector Usage

Illumination of the LACE satellite's retroreflector array was approved by SDIO for the following groups:

- Defense Space Technology Division, Jet Propulsion Laboratory
- Starfire Optical Range, USAF Phillips Laboratory
- Thermo Electron Technologies, San Diego, CA.

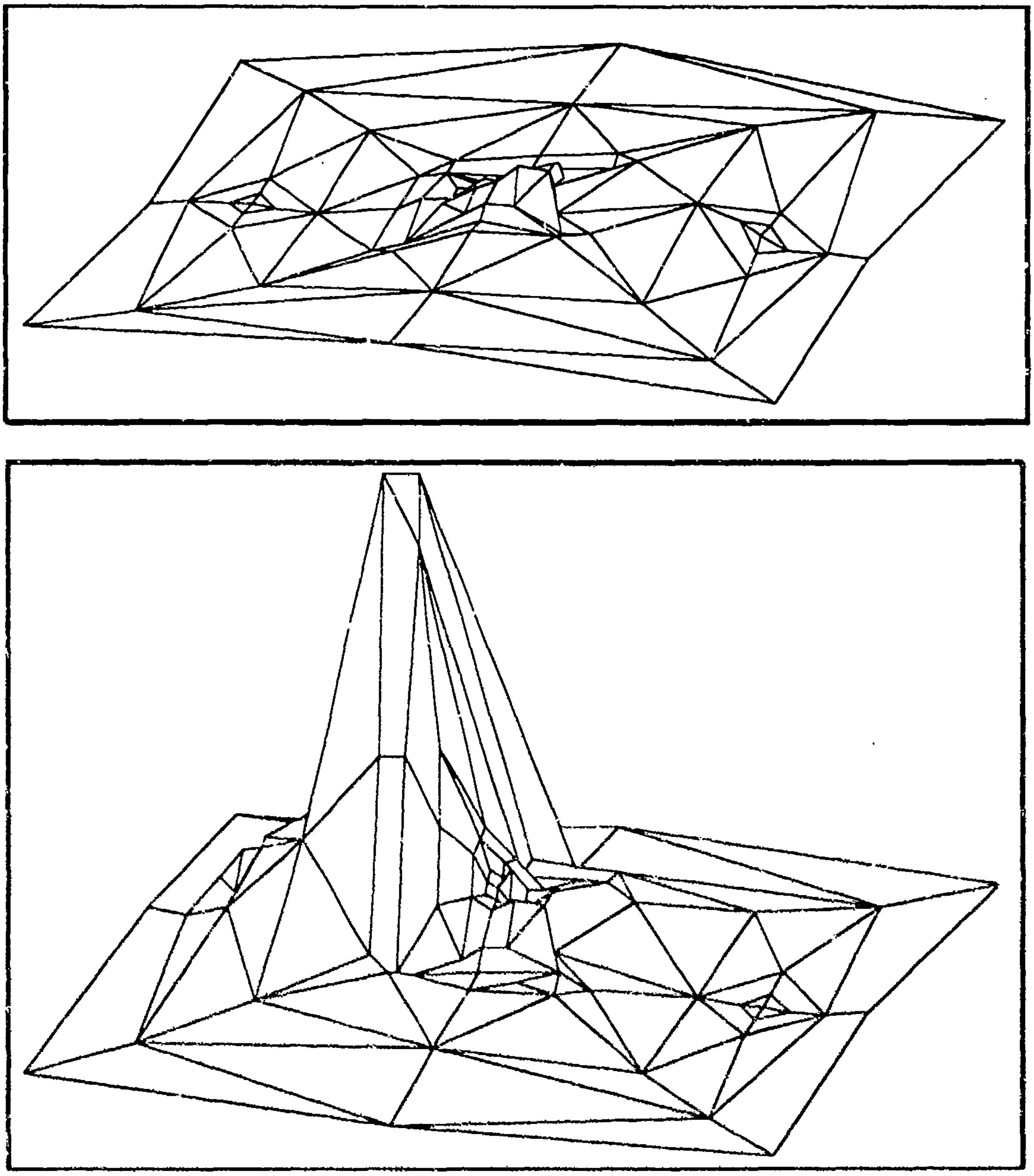

Fig. 2 - Qualitative effect of successful atmospheric compensation

Extendable Booms

The LACE satellite has three identical, variable-length booms that can be extended up to 150 ft. Although many booms had been flown on satellites prior to LACE, most had been extended only once to their desired length and not moved again. A variable-length boom of significant length had been flown on one shuttle mission, but it had been extended and retracted only a few times during the mission, which lasted approximately a week. The LACE satellite's booms had to extend and retract many times during the planned 30-month mission.

The leading and trailing booms on the LACE satellite were successfully extended and retracted more than 65 times over a 30-month period, with a range of lengths from 15 to 150 ft. A few boom motions involved a full extension or retraction, but most involved a smaller change in length. The gravity-gradient boom was left fully extended for more than 30 months before it was subjected to several partial retractions and extensions. This boom jammed at the 100-ft length during these final tests and could not be returned to its full extension. The cause of the jamming is not known. All boom length changes occurred at a rate between 0.1 and 0.3 ft/s, depending on spacecraft voltage level and tension in the boom. The booms were supplied by AEC-Able Engineering Company.

Boom Vibration Measurements

SDIO's Directed Energy Office (SDIO/TND) and the NASA Langley Research Center sponsored a series of tests in which the NRL Systems Analysis Branch and the Laser Radar Measurements Group of MIT/LL illuminated the LACE satellite to measure vibrations in the leading boom during and after motion. Several successful tests were conducted. The tests demonstrated a technique for obtaining data on large space structures (such as antennas, solar panels, radiators, and trusses) and provided data useful for validating dynamic, structural models of spacecraft in orbit.

In support of these tests, the LACE satellite carries two 1.5-in.-diameter and one 1-in.-diameter germanium cornercube retroreflectors. The 1-in.-diameter germanium cornercube retroreflector is mounted on the retroreflector array (Section 5.1). One of the larger retroreflectors is mounted on the Earth-facing panel of the main body of the spacecraft, and the other is mounted at the end of the trailing boom. Both of the larger retroreflectors have a filter to prevent retroreflection of wavelengths shorter than 5 μm to avoid interfering with atmospheric compensation tests. All three germanium retroreflectors point in the spacecraft's nadir direction.

To conduct the boom vibration tests, an argon ion laser operating with a wavelength of 514.5 nm illuminated the retroreflector array to provide a reflected signal for tracking and a narrowband, pulsed CO_2 laser operating at 10.6 μm functioned as a laser radar. Both lasers are located at MIT/LL's Firepond site near Westford, Massachusetts. Doppler measurements using the CO_2 laser could measure relative velocities as small as 3 mm/s between the boom tip and the spacecraft's main body.

The primary objective was to obtain vibration data for the leading boom. The leading boom was moved and data collected during and after the motion. Figure 3 shows boom tip motion relative to the spacecraft's main body during and immediately after retraction of the leading boom from a 32- to a 15-ft length in 67 s. This relative motion of the boom tip is a composite of pitch motion of the spacecraft at the orbital period, retraction of the boom, and vibrations induced by the retraction. The solid line in the figure is the modeled effect of the pitch motion and retraction contributions, as seen from the laser site.

Attitude Stabilization

Boom motion in support of the atmospheric compensation tests was expected to cause disturbances in the spacecraft's attitude, especially pitch. This was not a problem in using the SAS, but it became a problem with the later addition of the UVPI. For SAS use, the normal to the spacecraft's target board was required to be within 3° of nadir during the test, with a further requirement that it must be possible to later determine the actual attitude during the test to within 1°. For UVPI, the 2° field of view of the tracker camera required that the attitude of the spacecraft be known to less than 1° during the UVPI observation. Constraints of the UVPI use were frequently such that the best approach was to try to keep the spacecraft's attitude to within 1° of nadir at all times. However, the spacecraft's attitude control system was not designed to maintain the attitude to within 1° of nadir.

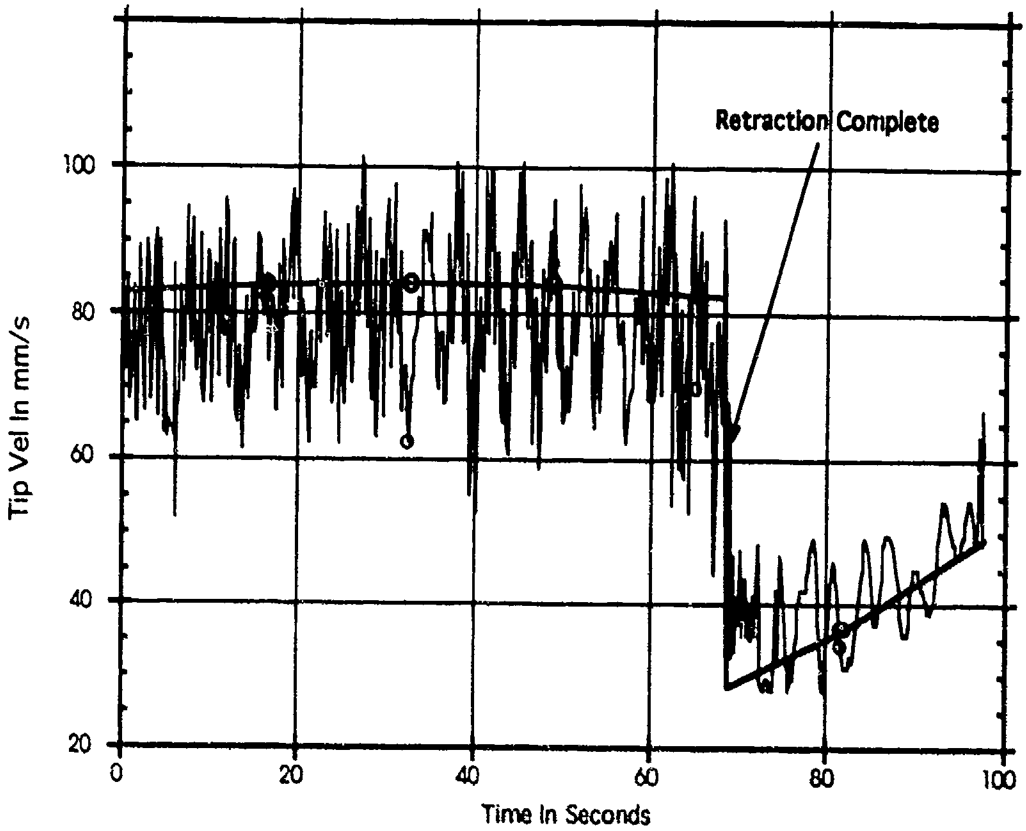

Fig. 3 - Leading boom tip motion relative to spacecraft's main body

During pre-launch analysis and simulation of the attitude oscillations, it became clear that pitch oscillations from boom motion were a result of the change in pitch attitude equilibrium position between the initial and final boom lengths. If a large change in boom lengths resulting in a relatively large change in pitch attitude equilibrium position was made quickly, the spacecraft would approach the final equilibrium position with significant pitch velocity, pass beyond the equilibrium position, and then oscillate about the final equilibrium position. The amplitude of this oscillation depended on the pitch velocity while passing through the final equilibrium position. If the booms were moved slowly, however, the pitch velocity while passing through the final equilibrium position was lower and the amplitude of the resulting pitch oscillation was smaller.

Slow boom motion to control pitch amplitude worked so well with the LACE satellite that its attitude was rarely more than 1° from nadir. Because the LACE satellite's booms could be moved only at one speed, slow boom motion was achieved by moving the booms in short intervals evenly distributed over a pitch oscillation period. The natural pitch oscillation period was approximately 71 min, but a forced pitch oscillation period at the orbital period was usually dominant.

If slow boom motion could not adequately control the pitch amplitude, a technique called deadbeating [4] was to be used to reduce the amplitude. This technique required that any of the three booms be retracted a short distance while the total pitch angular momentum was at or near minimum and extended back to its original position, or a nearby new position, when the total pitch angular momentum was at or near maximum. The total pitch angular momentum included, and was dominated by, the orbital angular momentum. However, the success of the slow boom motion technique meant that, to test the effectiveness of deadbeating, the opposite of deadbeating had to be used first to increase the pitch

oscillation amplitude. The deadbeating tests showed that, if rapid boom length changes were required such as to support the boom vibration tests described in Section 6.1, deadbeating could be easily used later to reduce the pitch oscillation amplitude to within 1° in a few hours.

The slow boom motion and deadbeating techniques were so effective that SAS or other tests involving boom motion could be conducted with confidence that a stable platform within 1° of nadir could be provided to support a UVPI observation 24 h later. Reference 5 describes the deadbeating tests and pitch attitude control of the LACE satellite through slow boom motion.

Navy Low Power Chemical Laser Tests

The Navy High Energy Laser Program Office (SPAWAR 232-1) planned a series of low-power, ground-to-space laser beam control and propagation tests using the SeaLite Beam Director, the LPCL, and the LACE satellite's SAS. The laser and beam director are located at the High Energy Laser System Test Facility (HELSTF) in White Sands, New Mexico. Because the TGS was not to be located at the laser site, extensive computer software was developed to quickly process IR sensor array data as it was received in the TGS at Vandenberg AFB so it could be transmitted over ordinary telephone lines to the laser site in time to allow them to use it to control their beam. Tapes of the unprocessed SAS data were to be provided later by the TGS, and all analysis of the SAS data was to be done by the Navy High Energy Laser Program Office. These were to be the final series of tests using the LACE satellite. However, authorization to conduct these tests was denied in January 1993.

6.2 UVPI-Related Accomplishments

Rocket Plume Observations

The UVPI collected high-quality, calibrated UV emission images from four rocket launches in four attempts. The seven high-altitude rocket plumes observed by the UVPI during the four launches were the third stage of the Special Project Flight Experiment 1 (SPFE 1) from Wallops Island, Virginia on 25 August 1990; the third and fourth stages of the Starbird Development Launch from Florida on 18 December 1990; the second and third stages of the Low Cost Launch Vehicle (LCLV) from Wallops Island on 6 February 1991; and the second and third stages of the Strypi rocket from Kauai, Hawaii, on 18 February 1991. The plume camera data obtained for these high-altitude plumes in the 195 to 295 nm and 220 to 320 nm bandpasses are not obtainable from the ground because it is blocked by Earth's ozone layer. These successful observations have provided more than 150 s of calibrated plume images from space. All UVPI plume observation data have been processed by the NRL LACE Program and archived in the SDIO Plumes Data Center at Arnold AFB, Tennessee, and the SDIO Backgrounds Data Center at NRL. Comprehensive NRL reports describing the plume observations and presenting the UVPI data [6-9] are being widely distributed to SDIO, to UVPI data users, and within the NRL LACE Program.

Figure 4 shows the UV emission in the 220 to 320 nm band of the third-stage plume of the SPFE 1 launch from a range of approximately 450 km. It is a composite image formed from the average contribution, after background subtraction, from each picture element in 72 frames collected over a 3.4-s time span. The image is a 32 by 32 picture element array enhanced by smoothing interpolation. The plume intensity has been mapped to a false-color scale with white representing the highest intensity. This image was used by *Aviation Week & Space Technology* magazine as the cover for their 8 April 1991 issue. All UVPI image processing for the NRL LACE Program was done by Applied Coherent Technology Corporation.

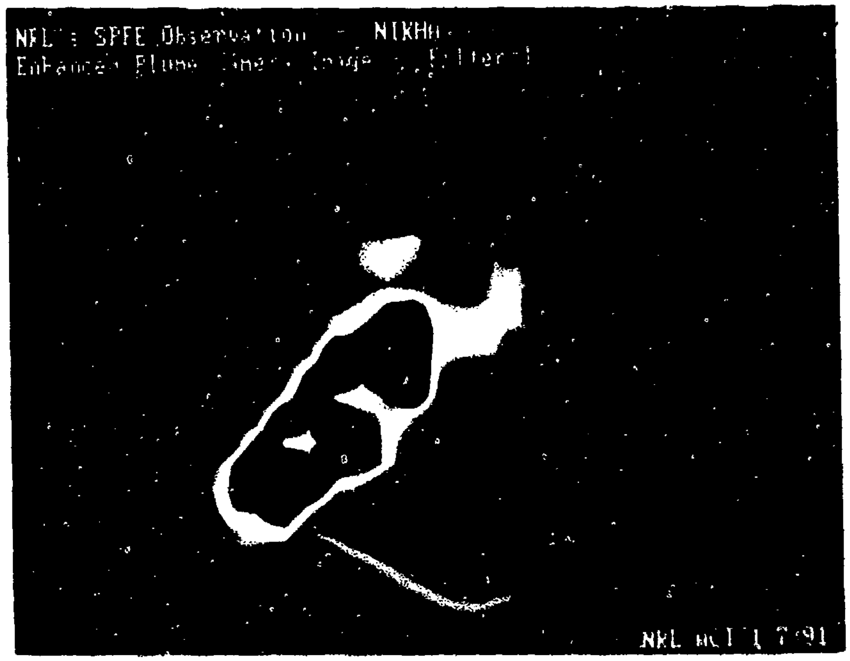

Fig. 4 Smoothed composite image of UV emission from rocket plume

Although the NRL LACE Program successfully observed plumes from four launches out of four attempts, interactions occurred on many more launches for which no data were obtained because the launch did not occur when the LACE satellite was nearby. Table 1 lists 18 launch opportunities for which some amount of cooperation by the launching program was expected or occurred and some effort was made to obtain UVPI images of the plumes. In some cases, such as the SPEAR II launch in July 1990, the UVPI team completed all planning and preparation, conducted four rehearsals, and carried out two observation attempts during which the rocket could not launch because an umbilical would not detach. The rocket launched approximately 24 h after the last observation attempt by UVPI, but the LACE passes over the launch site no longer fell within the launch window. In other cases, such as the DMSP launch in November 1990, the launching program made a decision to launch at a time when LACE was not nearby after significant planning and preparation had begun but before a rehearsal involving the LACE satellite had been conducted. All rehearsals listed in Table 1 involved the LACE satellite. The three shuttle entries in Table 1 pertain to observation attempts after the shuttle was in orbit and not to the actual launch of the shuttle. Attempts to observe plumes from the orbiting shuttle had a low expectation of success because

- two bodies traveling at orbital velocities were involved,
- the observation opportunity inevitably occurred away from LACE ground stations and had to be controlled by stored commands,
- the shuttle could and did change its orbit after the controlling commands were stored in the LACE satellite, and
- NASA could never guarantee that there would be plume generating activity during the few seconds of the observation opportunity.

Table 1 - UVPI Plume Observation Activity

Date		Target	Rehearsals	Observation Attempts	Comments
Mar	90	Titan	0	0	Launch outside LACE pass
Jul	90	SPEAR II	4	2	Launch outside LACE pass
Aug	90	SPFE 1 (Nihka)	3	1	Plume observed
Nov	90	Titan	3	0	Launch outside LACE pass
Nov	90	DMSP	0	0	Launch outside LACE pass
Dec	90	Shuttle	0	3	Daylight, remote; no plume
Dec	90	LCLV	1	0	Launch rescheduled
Dec	90	Starbird	3	1	Plume observed
Dec	90	LCLV	2	0	Launch rescheduled
Feb	91	LCLV	3	1	Plume observed
Feb	91	Strypi	5	1	Plume observed
Apr	91	SPFE 2 (Nihka)	5	0	Launch outside LACE pass
May	91	Shuttle	0	1	Night, remote; no plume
May	91	GBI/ERIS	3	0	Launch outside LACE pass
Jun	91	AST	3	0	Launch rescheduled
Jul	91	Pegasus	2	0	Launch outside LACE pass
Nov	91	Shuttle	0	0	Early return; no opportunity
Mar	92	Shuttle solid	2	1	Plume observed; ground burn

The successful observation of the ground burn of the shuttle solid rocket motor in March 1992 was not intended for collection of good UV plume data because the ozone layer was between the plume and UVPI. It was intended and used as a verification of the plume camera's filters.

In general, the investment of SDIO funding in a launch greatly enhanced cooperation by the launching program. The Starbird Development Launch was a supporting element of SDIO's Starlab Program, and imaging by UVPI was one of the launch's specific objectives. The Strypi rocket launch was funded by SDIO primarily to provide a target for UVPI. The LCLV launch was partially funded by SDIO. The SPFE launches were in support of another SDIO program. Imaging by UVPI was a minor objective for the SPFE 1 launch, and it was scheduled for a time when the LACE satellite was not in view. The launch was delayed by ground problems for almost two hours. When the problems were solved and launch was possible, a LACE satellite pass was only a few minutes away and the launch was then held for LACE. However, repeated cooperation by the Strategic Air Command (SAC) and NASA without SDIO funding was frustrated by primary mission constraints that were incompatible with imaging opportunities. One regret of the NRL LACE Program is that an opportunity never arose to obtain images of a plume from a liquid-fueled rocket.

Plume Observation Operations

Each of the plume observations involved extremely precise mission planning and operations techniques to deal with the split-second timing necessary to acquire and track missiles in midflight from an orbiting platform. Bendix Field Engineering Corporation, now AlliedSignal Technical Services Corporation, was responsible for all NRL LACE Program mission planning and operations. Barrios Technology Incorporated assisted with mission planning.

Attitude Prediction and Verification

The most difficult obstacle to successful plume observations was probably the LACE satellite's attitude sensors. The attitude control system and the attitude sensors were designed to support the SAS. For SAS use, the normal to the spacecraft's target board was required to be within 3° of nadir during the test, with a further requirement that it must be possible to later determine the actual attitude during the test to within 1°. For UVPI, the 2° field of view of the tracker camera required that the attitude of the spacecraft be known to less than 1° during the UVPI observation. The attitude sensors were modified after the addition of the UVPI. Initially, the attitude sensors comprised a sun sensor to provide the direction from the spacecraft to the sun, and a magnetometer to provide the orientation of the spacecraft with respect to Earth's magnetic field. The sun sensor was useless in darkness; the UVPI was designed for nighttime observations. An Earth horizon sensor, which could function in daylight and darkness, was added specifically to support the UVPI.

The horizon sensor provided roll and pitch measurements accurate to better than ±0.5°, but no yaw measurements. Also, there were yaw measurement discontinuities of approximately 1° as the satellite transitioned between daylight and darkness. Since the real-time attitude measurement uncertainty could be a few degrees, operational techniques had to be devised to improve the attitude knowledge. These techniques involved prediction of the spacecraft's pitch, roll, and yaw over many hours and real-time verification of the pitch, roll, and yaw by using UVPI itself to observe a star at the beginning of a plume observation pass.

The spacecraft's pitch, roll, and yaw varied in a rough sinusoidal pattern with a period usually at the orbital period. Approximately 3 h before a plume observation attempt, continuous attitude data from the previous 10 to 12 h would be analyzed to identify the sinusoidal patterns for pitch, roll, and yaw and to predict the spacecraft's attitude at the beginning of the plume observation pass and at the beginning of the plume observation itself. Based on these predictions, pointing functions for UVPI were calculated for a selected star and for the rocket plume. These prediction-based pointing functions were stored in the UVPI during a pass 1 to 2 h before the plume observation pass.

Stored commands turned on the UVPI, and the stored pointing function aimed it toward the selected star shortly before the spacecraft could communicate with the ground station on the plume observation pass. When the communication link was established, the selected star usually would be in the tracker camera's field of view. If the star was not seen by the tracker camera, a slight adjustment of the UVPI door mirror brought the star into the field of view. The planning and preparation phase for each plume observation included a calculation of the signal strength for the selected star, which was verified during the rehearsals by using the spacecraft and the UVPI. As soon as there was certainty that the selected star was within the field of view of the tracker camera, authorization to launch the rocket was given. For the Strypi launch, there were only 35 s between expected establishment of the communications link and scheduled launch time for the rocket.

Real-time attitude measurements were now available from the spacecraft, but the accuracy of the real-time yaw measurement was inadequate. Therefore, the gimbaled mirror in the UVPI was driven in a small-amplitude sinusoidal yaw pattern, and the times of transit of the selected star through the centerline of the field of view and the gimbal angles at centerline transit were obtained. Ground software quickly processed these data to provide an accurate yaw measurement for use in subsequent calculations during this plume observation pass. Usually the predicted values for pitch and roll agreed well with the real-time measurements, but a decision was made to choose either the predicted or the real-time pitch and roll values for subsequent calculations. The measured yaw value and the selected pitch and roll values were

then used to calculate a new pointing function for the selected star. This pointing function was quickly transmitted to the spacecraft and used to point UVPI's gimbaled mirror. Positioning of the selected star near the center of the field of view of the tracker camera verified that the selected attitude values were good. They were then used, along with the exact launch time of the rocket, to calculate a new pointing function for the rocket plume. During this calculation, the UVPI door was opened fully in preparation for the plume observation, and the proper filters and gain settings were selected by stored commands. The new pointing function for the rocket plume based on verified attitude data and actual launch time was transmitted and stored in UVPI.

References 10 and 11 provide a more detailed description of these operational procedures.

UVPI Gain Limit

During at least one rehearsal for a plume observation, the background scanned by the UVPI was virtually identical to the background that would be observed during the plume observation. The UVPI data from the rehearsals was examined to identify bright background objects seen by the tracker camera. Background objects nearly as bright or brighter than the plume could result in the UVPI tracking a bright background object and ignoring the plume. Operational procedures would then be devised to prevent tracking the wrong target. If the rocket plume was expected to be much brighter than any background object, the automatic gain control on the tracker camera was limited so that no background object could be detected, but the brighter plume would be detected. This was usually the case, and it provided an opportunity to obtain a few extra seconds of plume data.

Usually, the UVPI was first pointed at the rocket while the rocket was coasting between stages and there was no plume. A few seconds before ignition of the upper stage, the UVPI would be commanded to lock on any bright object in the field of view of the tracker camera. The limit on the automatic gain control ensured that no bright object was within the field of view and tracking lock was impossible. Then, as soon as the rocket ignited and a plume appeared, tracking lock would be established in response to the earlier command. Until tracking lock was established, the plume would not be within the field of view of the plume camera. This procedure was also used to ensure tracking lock at the moment of ignition of any subsequent stages. Without this procedure, the command to lock on a bright object had to be delayed until the UVPI operator in the ground station recognized the rocket plume in the transmitted tracker-camera image. This resulted in several seconds of lost plume camera data.

Background Observations

UVPI's observations of Earth background include southern auroral events, measurements of Earth's limb under different lighting conditions, day and night nadir scans, measurements near an erupting volcano, and measurements of emission from city and highway lighting. Observations of background phenomena are essential to the design of effective UV-based sensing systems. The UVPI data can help understand how much contrast there will be between a rocket plume and various background features and will identify background phenomena that could fool a sensing system.

Appendix A is a log of all UVPI observations. Of the 239 observations, 101 are identified specifically as background observations. Data from all UVPI observations have been processed by Applied Coherent Technology Corporation for the NRL LACE Program and deposited in the SDIO Backgrounds Data Center at NRL.

Although the UVPI was specifically designed for nighttime use with bright objects against a dark background, daytime nadir scans and measurements of Earth's limb were made in an attempt to extend the usefulness of the instrument and obtain needed data. A recent analysis of the daytime UVPI data for SDIO by The Johns Hopkins University Applied Physics Laboratory (APL) concluded that scattered light from extended sources beyond the field of view of the plume camera severely contaminated daytime limb and nadir observations. The results of this analysis are given in an unpublished APL report dated 25 September 1992, "UVPI Plume Camera Daytime Evaluation."

Joystick Control

An operator in a ground station can control the gimbaled mirror in UVPI by means of a joystick. While viewing the real-time images from the tracker camera, the operator can cause an object of interest to be centered in the tracker camera's field of view and, thus, bring it into the smaller field of view of the plume camera. This can be useful for targets that the tracking system is unable to lock on because they are diffuse or there is insufficient contrast with the background. The joystick's initial purpose was to allow plume camera observations of rocket plumes in daylight. The operator can hold weak targets within the field of view of the plume camera or cause the plume camera to scan extended targets. Tests using the joystick demonstrated that this could be done easily after only a little training and practice. Control buttons on the joystick could be given various functions, such as transferring tracking control to UVPI if the UVPI indicated that it was capable of closed-loop tracking.

Radar-Enhanced Tracking of Plumes

Radar-enhanced tracking of plumes (RETOP) involved using data from a launch site's radar to indicate the direction and distance of the rocket with reference to the center of the tracker camera's field of view. This information was displayed as a cursor superposed on the real-time tracker-camera image used by the joystick operator. If the target was beyond the field of view of the tracker camera, the cursor would be located at the edge of the image and indicate the relative azimuth to the target. The operator could use the joystick to bring the cursor to the center of the tracker camera's field of view. RETOP was useful for assuring that UVPI was pointing at a rocket while it was coasting between stages.

6.3 ABE-Related Accomplishments

Operational interactions between the NRL LACE Program and LANL gave assurance that the ABE hardware worked as designed, and highly successful measurements of the neutron background in space were made almost continuously following launch. All ABE data have been delivered to LANL for processing and analysis. References 12 through 14 describe the ABE instrument and provide results of the data analysis.

6.4 RDE-Related Accomplishments

RDE made measurements over 14 months, and all data were turned over to The Aerospace Corporation for processing and analysis.

6.5 Program Honors

The NRL LACE Program received letters of commendation from two Directors of SDIO, Lt. Gen. James A. Abrahamson and Ambassador Henry Cooper, and from SDIO's Deputy Director for Technology, Dr. Michael D. Griffin.

In recognition of the NRL LACE Program, NRL was awarded the 1991 Strategic Defense Technical Achievements Laboratory Award of the American Defense Preparedness Association based on nomination by SDIO/TND.

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8.0 FUNDING HISTORY

The NRL LACE Program was sponsored by SDIO/TND. Table 2 summarizes the funding by fiscal year.

Table 2 - Funding by Fiscal Year

Fiscal Year	Funding ($M)
1985	1.0
1986	10.3
1987	13.5
1988	29.5
1989	22.7
1990	25.6
1991	20.8
1992	4.6
1993	0.6
Total	$128.6M

Included in the total of $128.5 million is $10.4 million that was sent to other programs, such as SWAT, at SDIO's direction. Not included in Table 2 is $4.1 million obtained from other sources with SDIO's knowledge. Net funding for the NRL LACE Program was $122.3 million.

9.0 LESSONS TO BE LEARNED

9.1 Rocket Plume Targets

There was significant expectation that rocket launching programs external to the NRL LACE Program, and even external to SDIO, could be persuaded to make minor adjustments in their launch times to allow the UVPI to observe their rocket plumes. Although there appeared to be willingness to cooperate for many launches, real cooperation never occurred unless observation by UVPI was a specific objective of the launch. Launch managers had a great desire to launch as soon as they were ready during their launch window. Short delays in launching could result in completely missing a launch opportunity if the weather suddenly changed or a plane, train, or ship entered a restricted area. Missed launch opportunities add cost and can jeopardize the success of a program. Realistically, no launch manager is going to hold a launch, even briefly, just to be cooperative because, by doing so, the launch program and the launch manager risk much, but can gain nothing.

9.2 Funding Continuity

Even on adequately funded programs, short-duration funding shortages occur that cannot be removed until the beginning of the next fiscal year. When satellite programs encounter these funding discontinuities, a decision is made to continue spending at an adequate level for pre-launch activities and absorb the funding shortage entirely within preparation for post-launch activities. There is usually no viable alternative unless the launch date is extended. The decision to absorb the funding shortage within preparation for post-launch activities can result in an inability to obtain hardware and software, and even personnel, critical to post-launch activities in a timely manner and disappointment with the post-launch performance. Minimal post-launch impact is seen as delays in processing data. The ultimate post-launch impact would be failure to obtain data from the spacecraft. This dilemma has been around since the beginning of the space age. It may not have a solution, but it must be recognized and managed.

10.0 ACKNOWLEDGMENT

The great success of the NRL LACE Program arose from the outstanding efforts of the many NRL and contractor personnel who designed, built, integrated, and tested the LACE spacecraft and its supporting ground elements; who planned and executed operations; and who processed, evaluated, and distributed the resulting data. This NRL-contractor team provided the NRL LACE Program with its ideas, its energy, its resourcefulness, and its dedication and worked each task until it was done right. To each person who helped make the NRL LACE Program a success, we say a heartfelt thanks.

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APPENDIX A
LOG OF UVPI OBSERVATIONS

Table A1 lists all UVPI observations. Data from all UVPI observations have been processed by Applied Coherent Technology Corporation for the NRL LACE Program and deposited in the SDIO Backgrounds Data Center at NRL. Data from the four rocket plume observations were also deposited in the SDIO Plumes Data Center, AEDC/SUT, Arnold AFB TN 37389.

Table A1 lists the revolution number and date of each UVPI observation, the primary subject or target of the observation, and a code identifying the purpose of the observation. The codes for the observations are as follows:

1 - Rocket plume observation or rehearsal
2 - Calibration by star or internal lamp
3 - Ground beacon observation
4 - Background observation
5 - UVPI system test

Some additional background data might be found within observations whose code is other than 4. For example, background data might be contained within an observation whose code is 1 because its purpose was to rehearse for a rocket plume observation.

Table A1 - UVPI Observation Log

Revolution	Date	Subject	Code
223	900301	Nadir scan, twilight clouds	4
283	900305	Ground lights, city and rural	4
298	900306	Calibration, internal lamp	2
312	900307	Ground lights, city	4
402	900313	Tracking, first attempt	5
405	900313	Terminator, daylit clouds	4
597	900326	Tracking test	5
597	900326	Calibration, star	2
613	900327	Nadir scan, night, Malabar	4
687	900401	Tracking, ground laser beacon	5
702	900402	Tracking, ground laser beacon	5
939	900417	Nadir scan and limb scan, night	4
953	900418	Cities and launch sites, night	4
995	900421	Aurora observation attempt	4
1040	900424	Ground lights, city and rural	4
1049	900425	Ground lights, city and rural	4
1062	900426	Calibration, star	2
1085	900427	Limb, daylit	4

Revolution	Date	Subject	Code
1143	900501	Tracking, ground laser beacon	5
1158	900502	Tracking, ground laser beacon	5
1173	900503	Tracking, ground laser beacon	5
1247	900508	Tracking, ground laser beacon	5
1262	900509	Tracking, ground laser beacon	5
1281	900510	Calibration, star	2
1357	900515	Calibration, star	2
1369	900516	Ground lights, city and rural	4
1457	900522	Calibration, stars	2
1475	900523	Night background over Vandenberg AFB	4
1563	900529	Night background over Kennedy Space Center	4
1584	900530	Calibration, stars	2
1606	900531	Nadir scan, daylit	4
1794	900613	Calibration, star	2
1824	900615	Nadir scan, limb scan, night	4
1872	900618	Nadir sweep, day	4
1879	900619	Calibration, star	2
1890	900620	Limb, nadir scan, night	4
1962	900624	Calibration, star	2
1963	900624	Ground scan, night	4
1992	900626	SAC Minuteman plume observation attempt	1
2076	900702	Calibration, internal lamp	2
2089	900702	Limb scan, dark	4
2098	900703	Limb scan, day	4
2184	900709	Calibration, stars	2
2213	900711	Limb scan, day	4
2230	900712	Volcano observation, active, Hawaii, day	4
2322	900718	Night background over White Sands	4
2322	900718	Ground beacon at White Sands	1
2337	900719	SPEAR II plume observation rehearsal	1
2366	900721	SPEAR II plume observation rehearsal	1
2381	900722	Ground scan	4
2409	900724	Calibration, stars	2
2425	900725	Limb scan, night	4
2439	900726	Calibration, stars	2
2530	900801	Calibration, stars	2
2555	900802	Aurora scan	4
2570	900803	Aurora scan	4
2585	900804	Aurora scan	4
2606	900806	Calibration, stars	2
2622	900807	Calibration, star	2
2636	900808	Calibration, stars	2
2651	900809	Volcano observation, active, Hawaii, day	4

Revolution	Date	Subject	Code
2728	900814	Calibration, star	2
2770	900816	Volcano observation, active, Hawaii, day	4
2785	900817	Volcano observation, active, Hawaii, day	4
2800	900818	Volcano observation, active, Hawaii, day	4
2807	900819	SPFE1 plume observation rehearsal	1
2822	900820	SPFE1 plume observation rehearsal	1
2837	900821	SPFE1 plume observation rehearsal	1
2897	900825	SPFE1 (Nihka) plume observation	1
3048	900904	Ground beacon	3
3078	900906	Ground beacon	3
3167	900912	Ground beacon	3
3182	900913	Ground beacon	3
3300	900920	Joystick test	5
3315	900921	Joystick test	5
3386	900926	Aurora	4
3670	901015	Ground beacon at PGS	3
3686	901016	Joystick test	5
3701	901017	Joystick test	5
3716	901018	Joystick test	5
3731	901019	Joystick test	5
3746	901020	Joystick test	5
3820	901025	Joystick test	5
3835	901026	Joystick test	5
3866	901028	Calibration, star	2
4060	901110	Titan plume observation rehearsal	1
4075	901111	Titan plume observation rehearsal	1
4090	901112	Titan plume observation rehearsal	1
4229	901121	Calibration, star	2
4423	901204	Calibration, star	2
4466	901206	Remote shuttle observation attempt	1
4491	901208	Remote shuttle observation attempt	1
4503	901209	LCLV plume observation rehearsal	1
4592	901215	Starbird plume observation rehearsal	1
4607	901216	Starbird plume observation rehearsal	1
4621	901217	Starbird plume observation rehearsal	1
4636	901218	Starbird plume observation	1
4654	901219	LCLV plume observation rehearsal	1
4669	901220	LCLV plume observation rehearsal	1
4968	910109	Calibration, star	2
4983	910110	Calibration, star	2
5195	910124	Terminator scan, backlit, dawn	4
5210	910125	Limb scan, backlit, near dawn terminator	4
5279	910129	Calibration, star and uniformity scan	2
5286	910129	Baghdad and Kuwait vicinity at night	4

Revolution	Date	Subject	Code
5294	910130	Calibration, star and uniformity scan	2
5301	910131	Baghdad and Kuwait vicinity at night	4
5321	910201	Calibration, star and dark field	2
5336	910202	Calibration, star	2
5351	910203	Calibration, star	2
5351	910203	LCLV plume observation rehearsal	1
5381	910205	Calibration, star	2
5381	910205	LCLV plume observation rehearsal	1
5396	910206	LCLV plume observation	1
5396	910206	Calibration, star	2
5487	910212	Calibration, star	2
5502	910213	Strypi plume observation rehearsal	1
5517	910214	Strypi plume observation rehearsal	1
5537	910215	Strypi plume observation rehearsal	1
5552	910216	Strypi plume observation rehearsal	1
5567	910217	Strypi plume observation rehearsal	1
5582	910218	Strypi plume observation	1
5597	910219	Calibration, star	2
5726	910228	Limb scan, night	4
5931	910313	Aurora	4
5946	910314	Aurora	4
5961	910315	Aurora	4
5976	910316	Aurora	4
5991	910317	Aurora	4
6411	910414	SPFE2 plume observation rehearsal	1
6426	910415	SPFE2 plume observation rehearsal	1
6441	910416	SPFE2 plume observation rehearsal	1
6456	910417	SPFE2 plume observation rehearsal	1
6533	910422	RETOP test	5
6548	910423	RETOP test	5
6563	910424	RETOP test	5
6578	910425	RETOP test	5
6740	910504	Shuttle plume observation attempt	1
6786	910508	GBI/ERIS plume observation rehearsal	1
6801	910509	GBI/ERIS plume observation rehearsal	1
6816	910510	GBI/ERIS plume observation rehearsal	1
6994	910522	Nadir scan, day	4
7009	910523	Nadir scan, day	4
7024	910524	Nadir scan, day	4
7200	910605	Ground beacon at PGS and Wallops Island	3
7215	910606	Ground beacon at PGS and Wallops Island	3
7248	910608	Limb scan, night	4
7263	910609	Limb scan, night	4
7324	910613	Point spread measurements, ground beacon at Table Mountain	5

Revolution	Date	Subject	Code
7338	910614	Point spread measurements, ground beacon at Table Mountain	5
7365	910616	AST plume observation rehearsal	1
7380	910617	AST plume observation rehearsal	1
7395	910618	AST plume observation rehearsal	1
7410	910619	Dark field data	5
7487	910624	SAC Minuteman III plume observation rehearsal	1
7502	910625	SAC Minuteman III plume observation rehearsal	1
7812	910715	Dark field data; light leakage through door test	5
7816	910715	Pegasus plume observation rehearsal	1
7828	910716	Contrail observation attempt; daylit clouds	4
7831	910716	Pegasus plume observation rehearsal	1
7846	910717	Plume observation attempt (canceled)	1
7846	910717	Dark field test	5
7865	910718	Red leakage test (Kuwaiti oil fields at night)	5
7880	910719	Red leakage test (Kuwaiti oil fields at night)	5
7895	910720	Red leakage test (Kuwaiti oil fields at night)	5
8138	910805	Kuwaiti oil field fires, night	4
8153	910806	Kuwaiti oil field fires, night	4
8172	910808	Calibration, star	2
8187	910809	Calibration, star	2
8187	910809	Off-axis rejection	5
8336	910818	Red leakage test (red star)	5
8351	910819	Red leakage test (red star)	5
8379	910821	Aurora	4
8394	910822	Aurora	4
8409	910823	Aurora	4
8424	910824	Aurora	4
8665	910909	Nadir scan, day; dark field effect	5
8739	910914	Calibration, star	2
8754	910915	Calibration, star	2
8772	910916	Peacekeeper plume observation rehearsal	1
8873	910923	Door and PSF measurements	5
8888	910924	Door and PSF measurements	5
9037	911004	Rehearsal for ground firing plume	1
9052	911005	Ground firing plume observation attempt	1
9250	911018	Nadir stare, day	4
9265	911019	Nadir stare, day	4

Revolution	Date	Subject	Code
9280	911019	Nadir stare, day	4
9329	911023	Kuwaiti oil field fires. day	4
9344	911024	Kuwaiti oil field fires, day	4
9400	911027	Star extinction	4
9404	911028	Star extinction	4
9423	911029	Star extinction	4
9532	911105	Nadir stare, day	4
9547	911106	Nadir stare, day	4
9597	911109	Star extinction	4
9627	911111	Star extinction	4
9695	911116	Ground laser scattering	4
9710	911117	Ground beacon	3
9725	911118	Ground beacon	3
9740	911119	Calibration, star	2
9740	911119	Ground beacon	3
9878	911128	Star extinction	4
9951	911203	Calibration, star	2
10031	911208	Star extinction	4
10055	911209	Aerosol layer, day limb	4
10085	911210	Aerosol layer, day limb	4
10160	911216	Nadir stare, day	4
10175	911217	Nadir stare, day	4
10193	911218	Limb scan, terminator, remote	4
10208	911219	Star extinction	4
10215	911220	Limb scan, terminator, remote	4
10502	920108	Calibration, star	2
10517	920109	Calibration, star	2
10533	920110	Extended dark field test	5
10637	920117	Limb, night	4
10699	920121	Extended dark field test	5
10731	920123	Door test	5
10746	920124	Door test	5
10770	920125	Star extinction	4
10832	920129	Limb scan, terminator	4
10848	920130	Limb scan, terminator	4
10861	920131	Star extinction	4
10944	920206	Limb scan, backlit terminator	4
10959	920207	Limb scan, backlit terminator	4
11026	920211	Dark field test	5
11039	920212	Star extinction	4
11059	920213	Nadir stare, day	4
11074	920214	Nadir stare, day	4
11095	920216	Limb scan, backlit terminator	4
11185	920222	Star extinction	4
11228	920224	Nadir stare, day	4
11243	920225	Nadir stare, day	4
11266	920227	Calibration, star	2
11281	920228	Door test, clock test	5

Revolution	Date	Subject	Code
11351	920303	Volcano observation, Chile, day	4
11366	920304	Volcano observation, Chile, day	4
11382	920305	Star extinction	4
11493	920313	Pulsar observation	4
11569	920318	RSRM plume observation rehearsal	1
11584	920319	RSRM plume observation rehearsal	1
11599	920320	Plume observation, RSRM ground burn	1
11613	920321	Large Magellanic Cloud observation	4
11654	920323	Aurora	4
11669	920324	Aurora	4
11684	920325	Aurora	4
13173	920701	Limb scan, night	4
13741	920807	Calibration, star	2

GLOSSARY

ABE	Army Background Experiment
AFB	Air Force Base
APL	Applied Physics Laboratory
AST	Airborne Surveillance Testbed
BATCAVE	Bendix Alexandria Technical Center for Aerospace Vehicle Experiments
CW	continuous wave
DMSP	Defense Meteorological Satellite Program
HELSTF	High Energy Laser System Test Facility
Hz	Hertz
IR	infrared
J	Joule
kbps	kilobits per second
LACE	Low-power Atmospheric Compensation Experiment; Laser Communications Experiment
LANL	Los Alamos National Laboratory
LCLV	Low Cost Launch Vehicle
LDEF	Long Duration Exposure Facility
LOCF	LACE Operations Control Facility
LOTB	LACE Operational Test Bed
LPCL	Low Power Chemical Laser
Mbps	megabits per second
MIT/LL	Massachusetts Institute of Technology Lincoln Laboratory
NASA	National Aeronautics and Space Administration
NRL	Naval Research Laboratory
PGS	permanent ground station
PSF	point spread function
RDE	Radiation Detection Experiment
RETOP	radar-enhanced tracking of plumes
RME	Relay Mirror Experiment
RSRM	redesigned solid rocket motor
SAC	Strategic Air Command
SAS	sensor array subsystem
SDIO	Strategic Defense Initiative Organization
SDIO/TND	SDIO Directed Energy Office
SPFE	Special Project Flight Experiment
SWAT	Short Wavelength Adaptive Techniques
TGS	transportable ground station
UMPAC	UVPI Mission Planning and Assessment Center
USAF	United States Air Force
USASDC	United States Army Strategic Defense Command
UV	ultraviolet
UVPI	Ultraviolet Plume Instrument
VHF	very high frequency
W	Watt